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Droplet assisted laser micromachining of hard ceramics

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ABSTRACT

Hard ceramic materials like tungsten carbide (WC) are extensively used in high value manufacturing, and micromachining of these materials with sufficient quality is essential to exploit its full potential. A new micro-machining technique called droplet assisted laser micromachining (DALM) was proposed and demonstrated as an alternative to the existing nanosecond (ns) dry pulse laser ablation (PLA). DALM involves injecting liquid micro-droplets at specific frequency during the nanosecond laser micromachining to create impulse shock pressure inside the laser irradiation zone. The impulse shock pressure is generated due to the explosive vaporisation of the droplet, during its interaction with high temperature laser irradiation zone. In this paper, the DALM uses a nanosecond pulsed Nd:YAG laser to machine tungsten carbide substrate. The results suggest that the impulse shock pressure generated during the DALM process can transform the melt ejection mechanism of the ns laser micromachining process. The change in ejection mechanism results in a 75% increase in material removal rate and 71% reduction in the spatter redeposited compared to conventional dry ns laser micromachining.

1. Introduction

Hard, advanced ceramic materials such as tungsten carbide (WC) have excellent mechanical and thermal properties, including hardness, wear resistance and retention of strength at elevated temperatures, making them suitable for a wide range of applications from aerospace to tooling. It is these properties that make micromachining of WC challenging by conventional means and machining these materials is essential to fully realise their potential. Across a number of industries there is an increasing demand for components with both micro-scale features and the excellent properties afforded by modern day advanced ceramics. New fabrication techniques have been developed to improve micromachining, including ion-beam, electrical discharge and laser micromachining [1].

Micromachining using short (microsecond-nanosecond) and ultra-short (picosecond-femtosecond) pulsed lasers is becoming an important process to machine hard materials like WC. Dry pulse laser ablation (PLA) by nanosecond lasers is extensively used across range of industries [2], however significant spatter re-deposition and thermal damage was reported [3] at higher material removal rate (MRR). Ultrashort pulse laser machining using picosecond (ps) and femtosecond (fs) lasers is portrayed as an alternative to ns laser machining, however high frequency ultrashort pulse laser machining cannot be used for thick materials due to plasma shielding effect [4], its MRR is typically less than ns machining and is currently used mostly for micromachining of thin materials [4]. Moreover the cost of ultrashort pulse lasers is of an order of magnitude higher than similar average powered ns lasers.

The mechanism of dry ns PLA involves substrate absorption of laser fluence followed by melt pool formation, partial vaporisation and ejection of melt pool by vapour pressure. In dry PLA only part of the melted material is vaporised or ejected and the rest resolidifies inside the laser irradiated zone as a recast layer. Also, a considerable quantity of the ejected material is redeposited as dross (or spatter), around the edge of the micromachined region (over the material surface) [5–7]. In typical ns laser micromachining the material removal rate is inverse proportional to the micromachining quality [8].

Synova has developed a micro-jet based laser drilling, in which, a ns Nd:YAG laser beam travels co-axially to a water jet [9]. The water jet helps to address the residual heat build-up during conventional nanosecond laser processing. This process produces good quality micromachining [10]. However, the micro-jet process is slower than dry ns PLA, cannot be used with all laser wavelength, cannot be used with high powers lasers and has disadvantage of being a wet process. A recent development in ns PLA is the underwater laser process, in which the substrate is submerged in a liquid medium [3]. Studies have shown that the underwater laser pro-

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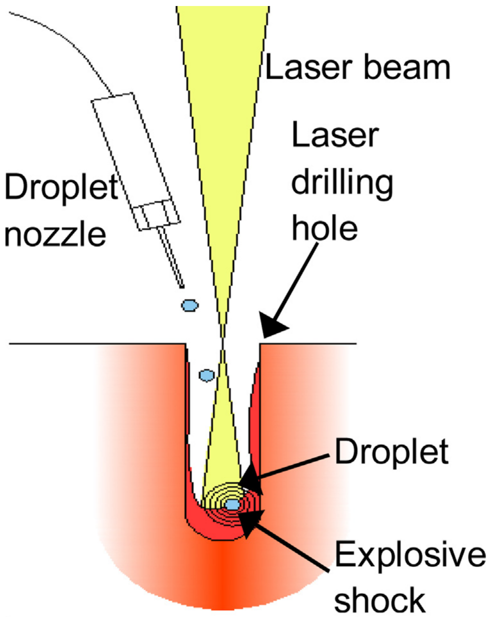


Fig. 1. Schematic of DALM setup.

cess helps to control the residual heating and decrease the spatter deposition; however maintaining a uniform water layer thickness is a challenging and the process has the practical disadvantages of being a wet process.

This paper reports preliminary investigations into the droplet assisted laser micromachining (DALM) process for micromachining of WC material. The droplet assisted laser micromachining process exploits the combined potential of conventional ns laser processing, shock processing [9] and wet processing [3,10], through the use of fine liquid droplets of size 150 μm. Though, this paper focuses on machining of WC ceramics, the DALM process should be applicable to most metals, alloys and ceramics.

2. Experimental procedure

Tungsten carbide blocks (P10 grade) of dimension 50 mm × 40 mm × 10 mm were used as test samples. The P10 grade is the standard tool material used for finish pass machining of steel components. Laser micromachining was performed with and without liquid droplets, so as to evaluate the performance of DALM based micromachining compared to conventional dry PLA process [4]. A schematic diagram of the DALM setup is shown in Fig. 1. Compared to the conventional dry PLA experimental setup, the DALM based micromachining system has an additional liquid dispenser (micro-dispenser) capable of delivering a controlled volume of liquid at a specific frequency and time. The micro-dispenser was used to inject the liquid droplets over the laser irradiation zone (to induce shock and remove the dross and recast layer). The frequency of the laser beam and micro-dispenser were synchronised to work in sequence. The laser source used for this experiments is a LITRON frequency tripled Q-switched Nd:YAG laser with a wavelength of 355 nm, maximum pulse frequency of 10 Hz and a pulse duration of 8 ns. Water was used as the liquid medium. A three axis linear stage was used to move the sample relative to the droplet/laser focus. All experiments were performed under ambient conditions without the influence of any assist gas [3,12].

The droplet dispenser has a nozzle exit diameter of 150 μm and was operated at 0.4 bar water pressure and 30 ms nozzle on-time. For all experiments the diameter of the droplet were maintained at 150 μm which was optimal for the droplet dispenser and the frequency was chosen to match the maximum laser pulse frequency of 10 Hz. A strobe light along with a CCD camera was used to identify the path of the droplets, and to ensure that the droplet hits the laser irradiated zone. The initial laser micromachining experiments were performed both with and without droplets to choose the range of the experimental parameters. The laser fluence was varied from 0.1 to 6 J/cm^2 and the number of pulses per position was varied from 25 to 500, to understand the significance of DALM and the conventional dry PLA process. All experiments were performed with a stationary laser beam and a stationary work piece. Finally, the laser micromachined samples were analysed using optical microscopy, scanning electron microscopy (SEM), elemental energy dispersive spectroscopy (EDX) and a white light interferometer.

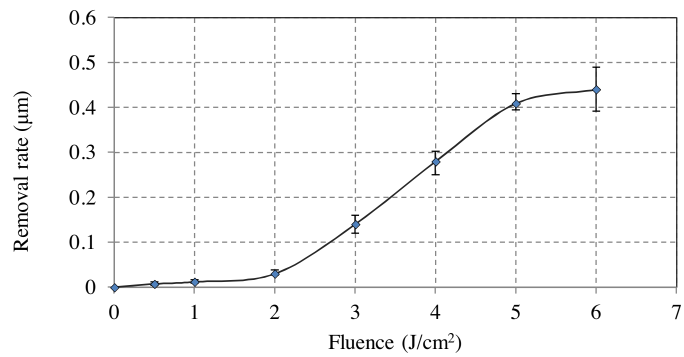


Fig. 2. Graph showing effect of laser fluence on removal rate for DALM (No of laser and droplet pulse = 250; Laser frequency = 10 Hz; Droplet frequency = 10 Hz).

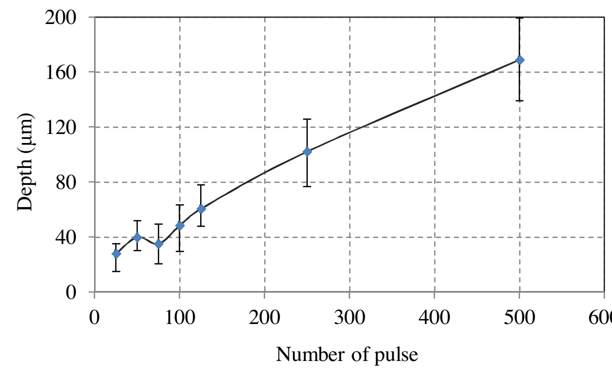
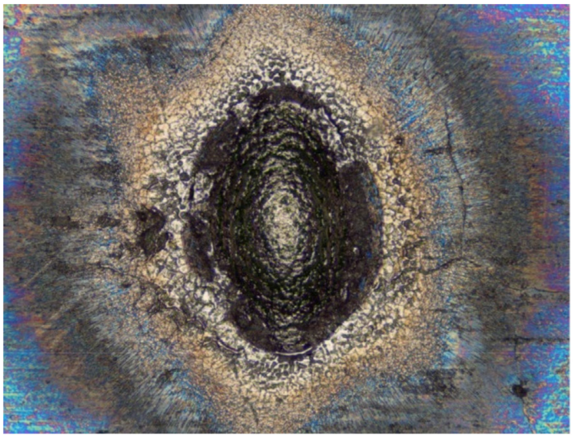


Fig. 3. Graph showing effect of number of pulse on the depth for DALM (Laser fluence = 5J/cm^2; Frequency = 10 Hz).

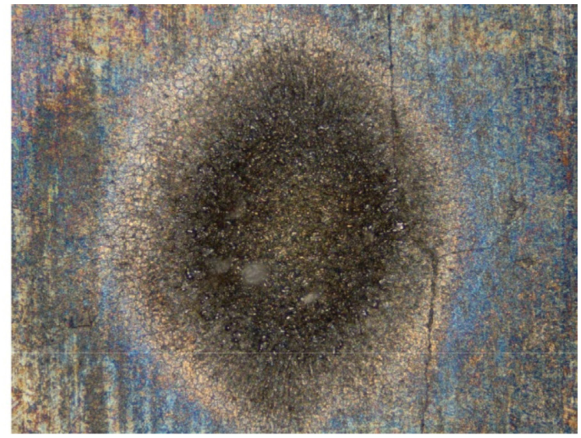
3. Results

The ablation rate of DALM based laser micromachining process, performed on a flat WC plate is shown in Fig. 2. As can be seen from the figure, a positive correlation was observed with increase in fluence; however the variance is amplified at the high fluence range of ~2–5 J/cm^2. As elucidated from the figure, the ablation threshold of the WC with DALM based laser micromachining process is close to 2 J/cm^2. A fluence of 5 J/cm^2 was chosen for further experiments due to its high material removal rate compare to the threshold ablation fluence. Also noticed from the figure is that the ablation rate becomes saturated above 5 J/cm^2, which is likely to be due to plasma shielding effects. The ablation trend of DALM based laser micromachining is similar to the one observed with dry PLA process, however, the magnitude of removal rate is significantly higher in DALM based process [4,6,11].

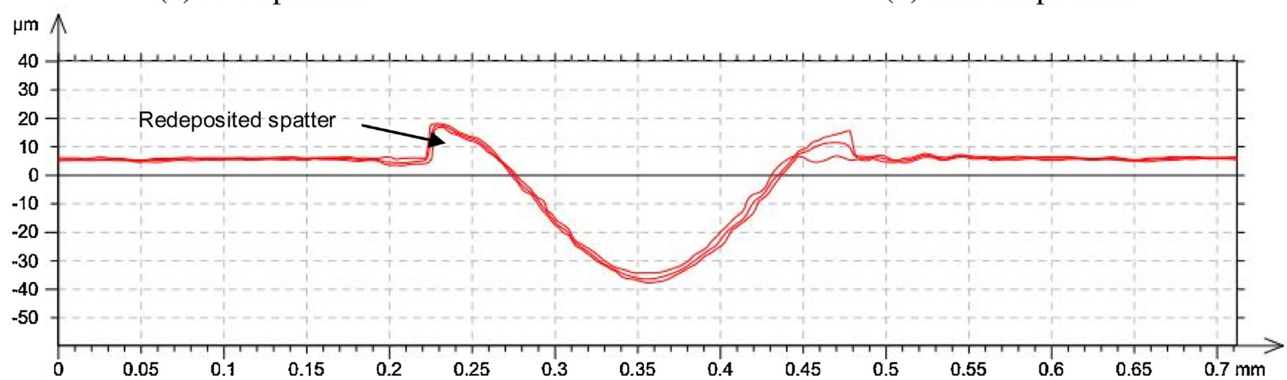
Fig. 3 shows the effect of laser pulse per position on ablation depth. As can be seen from the figure a strong linear relationship



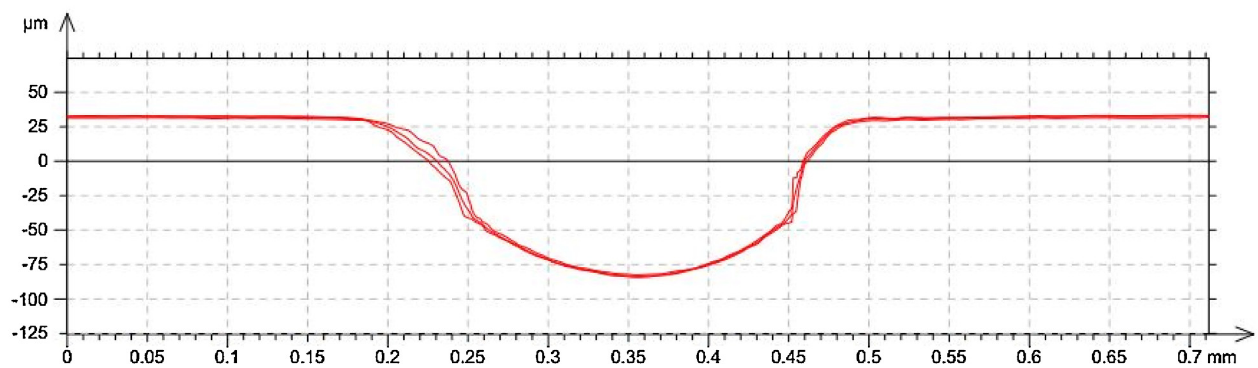
(a) PLA process



(b) DALM process



(c) Cross sectional surface profile of PLA process



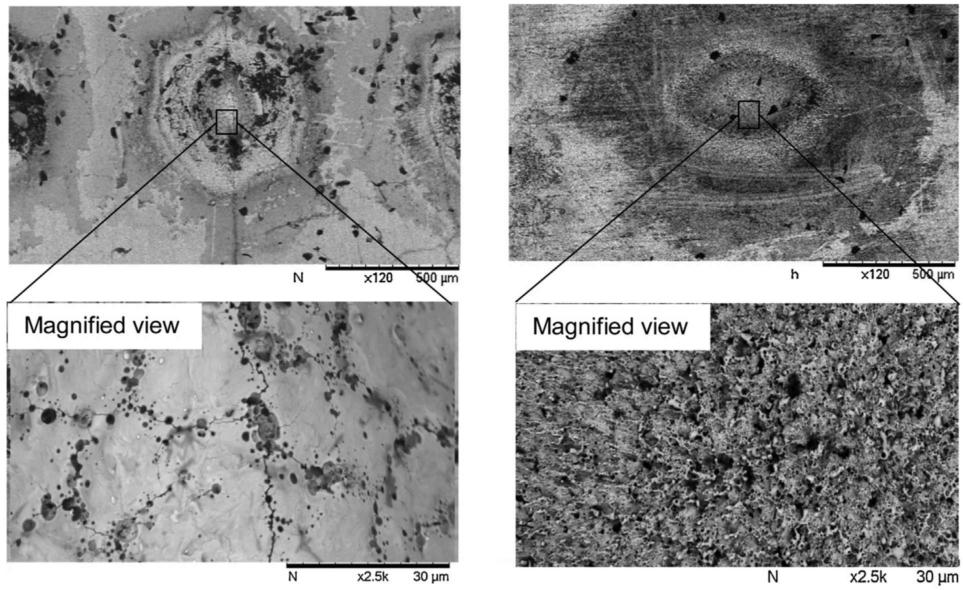
(d) Cross sectional surface profile of DALM process

Fig. 4. Images taken by the infinite focus optical microscope (Number of laser and droplet pulses = 125; Laser frequency = 10 Hz; Droplet frequency = 10 Hz; Laser fluence = 5J/cm^2).

between ablation depth and number of pulse per position was noticed. On average, the same amount of material was removed per pulse regardless of the total number of pulses. This suggests that, at the operating frequency of 10 Hz, the effect of the previous pulse has completely dissipated in the interval between pulses.

Fig. 4 shows a typical comparison of WC micromachining performed using conventional dry laser ablation process and the droplet based micromachining process. As can be seen from the figure, DALMS process shows high penetration and significant reduction in spatter redeposited over the edge of the hole.

Fig. 5 shows the surface characteristic of the DALM based and conventional dry pulse laser ablated region at low and high magnification. At high magnification, the DALM based surface appears rougher. The apparent lack of a resolidified layer is evidence to support the enhanced melt ejection mechanisms of the DALM process. SEM imagery of the DALM surface suggests that the remnants of the melt pool solidified whilst moving at high velocity. A pattern resembling turbulent fluid motion was observed for the DALM process, which is completely different from the PLA surface. The PLA surface shows a metallic like region, which is a recast layer. This clearly indicates that the addition of water droplets have sig-



(a) PLA process (b) DALM process

Fig. 5. SEM imagery of the laser machined region.

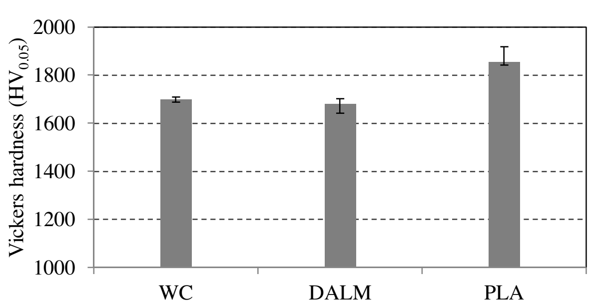


Fig. 6. Comparison of Micro-hardness.

Table 1
Effect of number of pulse per position on MRR for DALM and PLA (Fluence = 5J/cm^2; Frequency = 10 Hz).

No of pulses	Material removal rate (μm^3/pulse)		% change
	PLA	DALM	
100	6166.4	9913.4	60%
125	6280.5	11685.7	88%
250	5895.7	12707.6	124%

Table 2
Effect of number of pulse per position on spatter redeposited for DALM and PLA (Fluence = 5J/cm^2; Frequency = 10 Hz).

No of pulses	Volume of the redeposited material (μm^3)		% change
	PLA	DALM	
100	158881	31706.3	−81%
125	128215.6	28249.6	−76%
250	91141.6	20790.6	−73%

nificantly changed the melt ejection process of nanosecond laser micromachining process.

Micro-hardness was performed to confirm the subsurface characteristic of the laser irradiated zone and is shown in Fig. 6. As can be seen from the figure, DALM process shows hardness similar to the base material, whereas the conventional process shows high hardness. The high hardness in the conventional process should be attributed to the resolidified melt layer (recast layer) over the laser machined region.

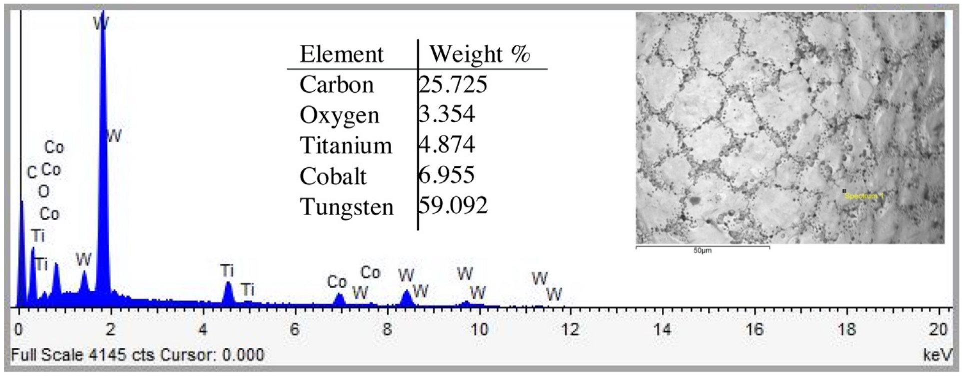
Further analysis by EDX was performed to assess the chemical composition of the laser irradiated surface and the results are shown in Fig. 7. In analysis for both processes there is a significantly higher than expected wt% of carbon whilst simultaneously a lower than expected wt% of tungsten although the combined percentage is around the expected value. The obvious outlier however is that 16.6 wt% oxygen was observed for DALM and 3.4 wt% oxygen was observed for dry PLA. Kruusing et al. [3] reviewed number of studies on underwater PLA and concluded that high intensity laser irradiation can excite the water molecules and result in oxide formation over the substrate surface. Though the absorption coefficient of water for UV laser wavelength is extremely low (1E–4 cm^{-1}), high laser intensity at the laser irradiated zone can result in non-linear absorption and subsequent oxide formation over the laser irradiated zone.

4. Discussion

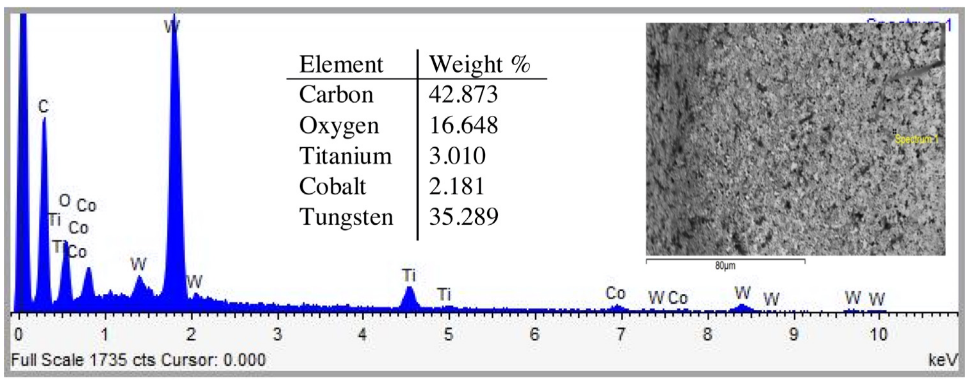
One of the key requirements of industrial laser micromachining is high productivity and quality, and the DALM based process demonstrates both of them. During UV laser micromachining of WC, the laser irradiated zone experiences a temperature in excess of 4000 K [6] with a melt pool of few micron thickness [6]. Interaction of the liquid droplet (of diameter 150 μm) with the high temperature laser irradiated zone can result in explosive vaporisation of liquid droplet and generation of impulse shock pressure.

Fig. 8 shows the 3D profile of the laser micromachined hole with DALM and dry PLA process. As can be seen from Figs. 4 and 8, the DALM process shows high penetration and less taper compared to conventional ns PLA, which suggest that DALM can be effectively used to machine thick material compared to conventional ns PLA

Table 1 and 2 shows the effect of number of pulse per position, on material removal rate and volume of material removed redeposited (estimated from the volume of the peak observed over the substrate surface) for DALM and dry PLA process. Analysis of the volume of material redeposited over the surface and the MRR

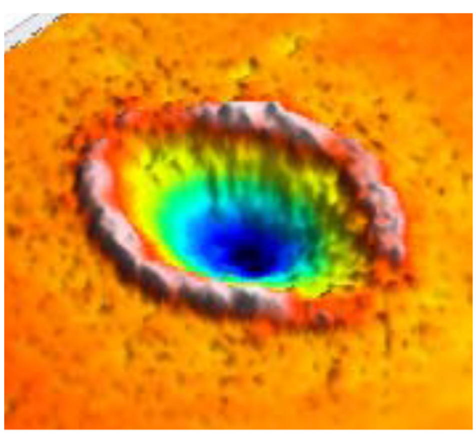


(a) PLA process

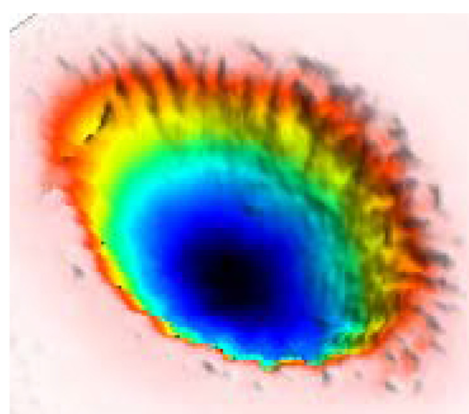


(b) DALM process

Fig. 7. EDX analysis for laser irradiated region.



(a) PLA process



(b) DALM process

Fig. 8. 3D profile of the hole machined with PLA and DALM.

revels that around 24% of material gets redeposited in dry PLA, whereas only 3% of material gets redeposited in DALM. This should be attributed due to the change in melt ejection mechanism of the DALM process.

Being a thermal process, the material removal in dry PLA is a combination of vaporisation followed by melt ejection (due to vapour press and phase explosion) [12]. In the region of the laser fluence discussed in this report, the melt ejection of PLA is caused predominantly by the recoil pressure of the vaporised material [13]. The recoil pressure in nanosecond laser micromachining is a function of ablation rate per pulse and laser fluence [14] (ablation rate per pulse is ~0.3 μm/pulse at 5 J/cm^2). Mscicki [15] estimated the recoil pressure in dry PLA to be around 0.3 GPa, which is significantly lower compared to the shock pressure generated during vaporisation of a liquid film which can be in the order of the order of 6.1 GPa [16]. In the DALM process, the melt ejection is due to the sum of recoil pressure and the shock pressure, generated during the explosive vaporisation of the liquid droplet. It seems, the higher pressure (sum of vapour pressure and shock pressure) inside the laser irradiated zone for the DALM increased the velocity and rate of the melt ejection process, which results in less spatter deposition and more material removal rate. Though the MRR is higher in the DALM process, due to the high ejection velocity, the spatter was not redeposited at the edge of the laser irradiated zone. In addition, the DALM based redeposited spatter had low adhesion over the substrate as they reach room temperature (due to high ejection velocity) before falling over the substrate.

The increased melt ejection improves the material removal rate of the DALM based process. As can be seen from Table 1, there is around 75% overall increase in material removal rate with the DALM process, a significant part will be due to the improved melt ejection mechanisms resulting in a minimal recast layer. It was clear from the optical microscopy that the addition of the liquid droplet significantly inhibited the spatter formation around the perimeter of the laser irradiated zone (as seen from Fig. 4). Based on the data from Table 2, 71% less material is redeposited onto the substrate as spatter in DALM process compared to PLA.

5. Conclusions

Experimental investigations were carried out to demonstrate and to understand the mechanism of droplet assisted laser micromachining process. Results have been presented with suitable illustrations. The following important conclusions could be drawn from the study.

- Droplet assisted laser processing can be used to achieve high quality and high material removal rate in laser micromachining of hard ceramic materials.
- Compared to dry PLA process, the DALM process can result in around 75% increase in material removal rate.
- DALM process can be used to perform micromachining with minimal taper and little or no spatter deposition. Compared to dry PLA process, DALM process result in 70% less material being redeposited on the surface.
- The improvement observed with the DALM system is attributed to the change in melt ejection phenomena, in particular, the explosive vaporisation of the droplet that helps to efficiently remove the melt layer at the side walls of the irradiated zone.
- The shock pressure generated during explosive vaporisation of the liquid droplet increases the melt ejection velocity, thereby reducing the spatter deposited over the ablated surface.
- A laser fluence of 5 J/cm^2 produces optimal material removal for both dry and DALM based laser micromachining of tungsten carbide. Within the operating range, the frequency of the laser source had no effect on laser machining characteristic.
- With further developments in the experimental setup and synchronization system the DALMS process can be readily used for micro-machining at industrial scale.

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